Sustainability analysis of rapid prototyping: material/resource and process perspectives

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Abstract: Sustainability of rapid prototyping (RP) depends on both model-building materials (wooden-materials, photo-resins, etc.) and model-building processes (additive processes – SLA, SLS, etc.; and subtractive processes – e.g., wood-sawing). In this study, a sustainability index is developed for RP processes, and this index incorporates such sustainability factors as volumetric quantity of model-building material, CO_2 footprint and resource depletion of primary production of model-building material, energy consumption and CO_2 emission of the model-building process. In addition, physical models have been created from the same 3D CAD data by using both SLA-based RP technology (additive process) and wooden-material-based RP technology (subtractive process). The subtractive process uses a specially designed CNC machine tool that removes the wooden-material using a circular-saw controlled by a 3D CAD model. The model-building process has been repeated for different scales of the same 3D CAD model. Using the experimental results, the sustainability index of the two RP technologies has been compared. The results help determine the critical size of a physical model of a given 3D CAD model and RP technology ensuring sustainability. In addition, the results show new avenues for improving the respective RP technologies in terms of sustainable manufacturing requirements.

Keywords: sustainable manufacturing; rapid prototyping; polymeric materials; wooden materials; additive manufacturing; subtractive manufacturing.

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1 Introduction

Sustainable manufacturing is concerned with the performances of product realisation processes/systems/equipments in terms of societal, economic, functional, and environmental aspects (Jovane et al., 2008). Both framework and metrics have been developed to ensure a fair and comprehensive evaluation of sustainability performance of manufacturing at the product, process and system levels (Jayal et al., 2010; Lu et al., 2011; Jawahir and Jayal, 2011). For manufacturing processes, in particular, it has been found that a substantial amount of environmental burden is generated from the primary production of materials, tools and devices (Ullah et al., 2011b). To improve the sustainability of manufacturing processes innovation plays an important role and new ideas and alternative approaches should be explored and implemented (Jawahir and Jayal, 2011; Ullah et al., 2011a).

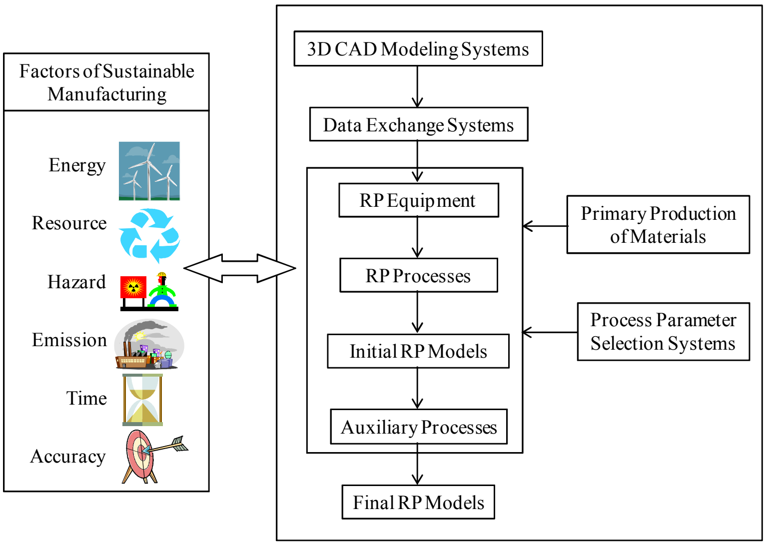
Nowadays, rapid prototyping (RP) has extensively been used in product realisation processes. RP produces physical models directly from 3D CAD models (Jacobs, 1992; Xue and Gu, 1996; Bourell et al., 2009) mainly for design review. Sustainable manufacturing provides a scope for analysing the RP model-building processes, systems, and equipment in terms of such factors as energy/resource/time consumption, greenhouse gas emission, safety, and accuracy (Kellens et al., 2011; Ullah et al., 2011a). In RP, additive manufacturing processes such as stereolithography (SLA), selective laser sintering (SLS), or laminated object manufacturing (LOM) are used to produce the physical models by adding fresh materials layer by layer. These processes are highly energy-intensive compared to other conventional manufacturing processes (Gutowski et al., 2009; Gutowski, 2010) Thus, for enhancing the sustainability of RP, conventional subtractive manufacturing processes (e.g., milling, turning, sawing, etc.) can also be considered. In this regard, wooden-material-based RP is one of the promising options (Ullah et al., 2011a).

The purpose of this study is to obtain a deeper insight into the sustainability of RP from the perspectives of both model-building materials (wooden-materials, photo-resins, etc.) and model-building processes (additive processes – SLA, SLS, etc.) and subtractive processes such as wood-sawing). The remainder of this paper is organised, as follows: Section 2 provides an overview of research in sustainable RP technology. Section 3 describes an index to quantify the sustainability of RP in terms of both model-building material and model-building process. Section 4 describes the eco-attributes of primary production of wooden- and polymeric materials, the usual model-building materials. Section 5 presents the experimental results of sustainability of model-building processes: SLA-based and wooden-material-based model-building processes. Section 6 provides a comparison between SLA-based and wooden-material-based RP technologies. Section 7 presents the concluding remarks of this study.

2 Research in sustainable RP

RP generally uses additive manufacturing processes (SLA, SLS, LOM, etc.) to create a physical model from a given 3D CAD model. Thus, the research in sustainable RP mainly focuses the materials, systems, and equipment used in additive manufacturing. Figure 1 schematically illustrates the facets of the research in sustainable RP. As seen from Figure 1, the sustainability of RP depends on the performance of 3D CAD modelling systems, data exchange systems, RP equipment, RP processes, process parameters selection systems, and primary materials production. Several authors have investigated the above facets and provided insights on the sustainability of RP in terms of energy/resource/time consumption, greenhouse gas emission, hazard, and accuracy. Some of the selected studies are summarised below.

Figure 1 RP and sustainable manufacturing (see online version for colours)



First consider the aspect of 3D CAD modelling systems. The first input of RP is a 3D CAD model. Before starting the physical model-building process (RP processes in Figure 1), one can make some design changes in the 3D CAD model to shorten the time needed for building the physical model. Before even building the 3D CAD model one can use less formal design information (e.g., 2D freehand sketch) to estimate the RP model-building time. If the estimated model-building time is quite long, one can easily make some design changes in the sketch to shorten in physical model-building time. This means that RP becomes more sustainable if the 3D CAD model-building systems accompany additional modules for estimating the physical model-building time from informal design information (e.g., freehand sketches). Campbell et al. (2008) developed a system that can predict physical model-building time from a 2D sketch.

As illustrated in Figure 1, another important facet of sustainable RP is the data exchange systems. The data exchange system makes a 3D CAD model meaningful to RP equipment. In particular, the data exchange system performs triangulation (facets) of the outer surface of a 3D CAD model (referred to as STL data) and slicing of such data. Thus, the performance of the data exchange systems affects the sustainability of RP in terms of time and accuracy. Many studies have been carried out on developing new algorithms for robust and error-free slicing, STL data compression, and direct slicing of 3D CAD models without using facets (Zhang et al., 2002, 2003; Pandey et al., 2003; Shi et al., 2004; Liu et al., 2009; Zhao et al., 2009; Hayasi and Asiabanpour, 2009).

RP process parameter selection system is also an important facet of sustainable RP. Once a user decides to use a particular RP technology (SLA, SLS, LOM, etc.), the user can utilise a process parameter selection system to optimise the model-building process by enhancing the productivity (time) and accuracy. Numerous studies have been carried out in this regard by providing various means to optimise such process parameters as layer thickness, layer planning, type of apparatus, laser dose, scanning speed, etc., for reducing time, cost, and energy consumption during the physical model-building process and during the auxiliary processes (Luo et al., 1999a, 1999b; Mognol et al., 2006; Drizo and Pegna, 2006; Kellens et al., 2011; Baumers et al., 2011a, 2011b; Gogate and Pande, 2008).

Since a physical model is made of a certain amount of fresh material, sustainability of primary production of model-building material is also an important facet of sustainable RP (Drizo and Pegna, 2006). This aspect has not yet been addressed properly, due to lack of information/knowledge, although there has been an active attempt for gathering material and process-related information (Kellens et al., 2011). It is worth mentioning that the photosensitive materials used in additive RP, particularly in SLA, require a minimum amount of time to get solidified. The solidification time depends on the laser intensity, layer thickness, and resin compositions (Lee et al., 2001; Aoki et al., 2011). Similar comments holds for SLS-based processes (Bourell et al., 2009; Baumers et al., 2011a, 2011b), i.e., a substantial amount of time is needed to complete additive manufacturing process. This makes the additive manufacturing process-based RP an energy-intensive process (Gutowski et al., 2009; Gutowski, 2010).

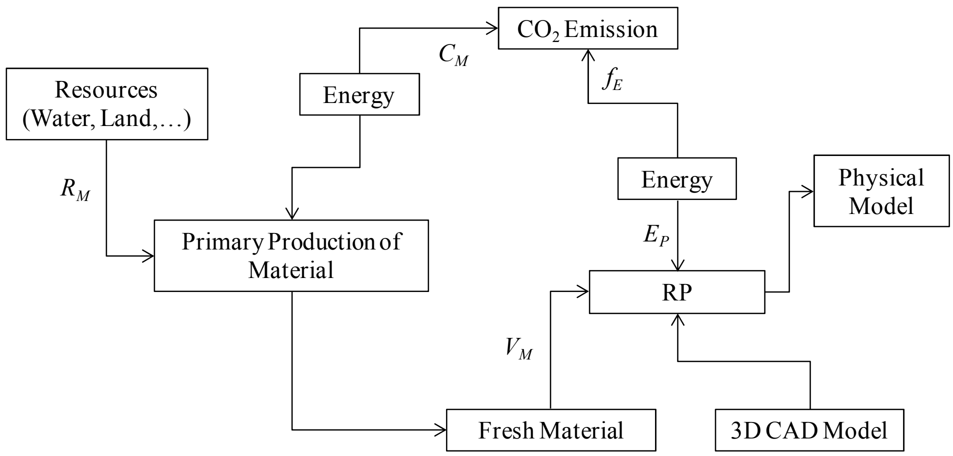
Thus, making improvements in 3D CAD modelling systems, data exchange systems, and process parameter selection systems is not enough for enhancing the sustainability of RP. Other possible alternatives might be explored, e.g., wooden-material-based RP (Ullah et al., 2011a; Gardan and Roucoules, 2011).

3 Quantifying sustainability of RP

A fair and comprehensive quantification of sustainability of manufacturing in general requires a set of well-defined metrics (Jayal et al., 2010; Lu et al., 2011; Jawahir and Jayal, 2011). RP technology is not an exception. However, since the physical models made by using a RP technology are just models, one can produce them in a desired scale. This means that the amount of fresh material might become a key element of sustainable RP. At the same time, an alternative approach (i.e., subtractive manufacturing) might be considered in parallel with additive manufacturing as a model-building process. Based on the above contemplation, a sustainability index for RP is developed and is described below.

Figure 2 schematically illustrates the scope of the proposed index. As seen from Figure 2, RP technology uses a 3D CAD model and consumes energy and fresh material to produce a physical model. The model-building process also results in CO_2 emission. The primary production of model-building material also consumes energy (thereby emits CO_2) and uses natural resources (water, land, etc.). Therefore, the proposed sustainability index for RP technology should incorporate both sustainability of model-building material and model-building process. As such, the amount of fresh material used to build a physical model, the CO_2 footprint and resource depletion of primary production of model-building material, and the amount of energy/CO_2 emission of model-building process are the major factors that needs quantification in the use of the proposed index.

Figure 2 Scope of the proposed sustainability index of RP



3.1 Basic formulation

Referring to Figure 2, let V_M (cm^3/model) be the amount of fresh material (volumetric quantity) used to produce a physical model, C_M (CO_2-kg/cm^3) be the CO_2 footprint of primary material production per unit volume of material, E_P be the energy consumption during the model-building process (kWh/model), and f_E (CO_2-kg/kWh) be the conversion factor for determining the equivalent amount of CO_2 for a unit energy consumption. The total CO_2 footprint of a RP model denoted by C_{RP} (CO_2-kg/model) is the summation of CO_2 footprint of primary production of model-building material and CO_2 emission from the model-building process, as follows:

$$C_{RP} = C_M V_M + E_P f_E \tag{1}$$

The conversion factor f_E depends on the geographical location. The model builder does not have any control over it. For example, in Hokkaido, Japan (the region wherein the authors conducted this study), f_E = 0.588 kg-CO_2/kWh (see, CO_2 Footprint of Electrical Energy Production in Japan, http://www.env.go.jp/press/press.php?serial=11956). This value is the same irrespective of the RP models built in Hokkaido.

The energy consumption E_P might vary with V_M. For the sake of analysis, let E_P be an exponential function of V_M expressed as

$$E_P = a\left(V_M\right)^b \tag{2}$$

The coefficients a and b determine the degree of dependence of E_P and V_M. For example, b = 0 means that E_P does not depend on V_M (a case for wooden-material-based RP, see Section 5) and b = 1 means that E_P linearly increases with the increase in V_M (a case for SLA-based RP).

Substituting E_P of equation (2) in equation (1) yields

$$C_{RP} = C_M V_M + a\left(V_M\right)^b f_E \tag{3}$$

In addition to the CO_2 footprint, to produce primary materials (i.e., V_M), natural resources are needed, e.g., land, water, and alike. Let R_M (amount of resource/unit volume of material) be a measure of resource depletion (e.g., R_M could be the amount of water needed to produce a unit volume of wood, polymer, etc.). Therefore, the following parameter denoted by S_{RP} (CO_2-kg-unit-resource/model) becomes the sustainability index of a given RP technology.

$$S_{RP} = C_{RP} \cdot R_{RP} V_M \tag{4}$$

Substituting C_{RP} of equation (3) in equation (4) yields:

$$S_{RP} = \left(C_M V_M + a\left(V_M\right)^b f_E\right) V_M R_{RP} \tag{5}$$

Needless to say that S_{RP} incorporates all: the amount of fresh material used to build the physical model, the CO_2 footprint and resource depletion of primary production of the model-building material, and the amount of energy/CO_2 emission of model-building process. Therefore, minimisation of S_{RP} enhances the sustainability of a given RP technology. This means that one can use S_{RP} to compare RP technologies, and also to find ways to improve the sustainability of a given RP technology.

3.2 Comparative index

Using the basic index defined in equation (5), a comparative index can be formulated to compare two given RP technologies assuming that both physical models have the same external volume. To do so, equation (5) needs rearrangement. First, the expression of S_{RP} is rearranged, as follows:

$$S_{RP} = \left(C_M R_{RP}\right) V_M^2 + \left(af_E R_{RP}\right) V_M^{b+1} = \alpha V_M^2 + \beta V_M^{b+1} \tag{6}$$

The quantities $C_M R_{RP} = \alpha$ and $af_E R_{RP} = \beta$ are two constants for a given model-building material, geographical location, and RP technology.

Referring to equation (6), S_{RP} can be reduced by reducing the volume of fresh material (V_M). This means that producing a small-scale RP model enhances the sustainability of a given RP technology. Since α and β are two constants (as mentioned above) for a given RP technology, geographical location, and model-building material, the following relationship holds:

$$\beta = d \cdot \alpha \tag{7}$$

As a result, d is expressed, as follows:

$$d = \frac{af_E}{C_M} \tag{8}$$

Therefore, the expression of S_{RP} can further be rearranged in the following manner:

$$S_{RP} = \alpha V_M^2 \left(1 + d V_M^{b-1}\right) \tag{9}$$

The expression in equation (9) is a useful expression that can be used to compare the sustainability of two given RP technologies. To do so, let A and B be two given RP technologies. For creating physical models having the same external volume, A requires V_{MA} amount of fresh material and B requires V_{MB} amount of fresh material. Thus, the following formulations hold:

$$S_{RPA} = \alpha_A V_{MA}^2 \left(1 + d_A \left(V_{MA}\right)^{b_A - 1}\right) \tag{10}$$

$$S_{RPB} = \alpha_B V_{MB}^2 \left(1 + d_B \left(V_{MB}\right)^{b_B - 1}\right) \tag{11}$$

For a given external volume of physical model, let V_{MA} and V_{MB} be are related, as follows:

$$V_{MB} = \rho \left(V_{MA}\right)^{\lambda} \tag{12}$$

Therefore, while comparing RP technology A with RP technology B, V_{MB} in equation (11) should be replaced by the equivalent V_{MB} in equation (12). This yields the following formulation:

$$S_{RPB} = \alpha_B \left(\rho^2 \left(V_{MA}\right)^{2\lambda}\right)\left(1 + d_B \left(\rho^2 \left(V_{MA}\right)^{2\lambda}\right)^{b_B - 1}\right) \tag{13}$$

For the sake of comparison, S_{RPA} calculated by using equation (10) and S_{RPB} calculated by using equation (13) should be compared. If S_{RPA} is smaller than S_{RPB}, then RP technology A is more sustainable than the other one (B).

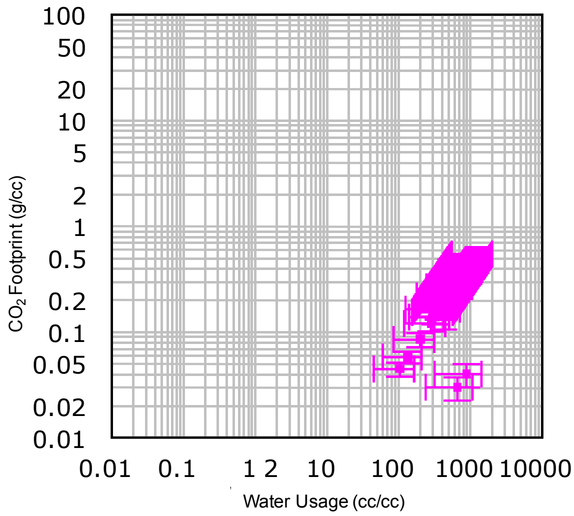
The remainder of this article provides numerical examples of sustainability of SLA-based RP technology (A) and wooden-material-based RP technology (B) in terms of the above proposed sustainability index.

4 Effect of model-building material

The effect of model-building material is incorporated into the sustainability index S_{RP} as described in the previous section by using two parameters C_M and R_M – see equations (4) to (6). Thus, one should use a material to build a physical model that has low C_M and R_M. Both photo-polymers (resins) and wooden-materials are often used to build physical models (Luo et al., 1999a, 1999b; Drizo and Pegna, 2006; Kellens et al., 2011; Ullah et al., 2011a; Gardan and Roucoules, 2011). Therefore, it is important to see the variability in C_M and R_M of photo-resins and wooden-materials.

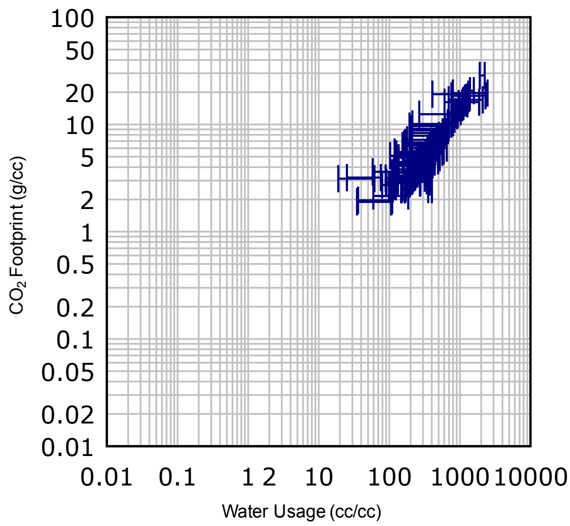
First, consider the case of wooden-materials. There are many types of wooden-material produced from the trees such as Alden, Ash, Bamboo, Birch, Maple, Oak, Pine, Redwood, Palm, and so on. For growing trees and ultimately producing wooden-materials, energy and resources (water and land) are needed. The total energy needed can be used to estimate the CO_2 emission referred to as CO_2 footprint of primary material production (Ashby, 2009). The material database supplied by the Granta Design (CES Selector, Version 5.1.0, http://www.grantadesign.com) has been searched and CO_2 footprint and water usage of primary material production of 447 selected wooden-materials have been determined. These results are plotted in Figure 3.

Figure 3 Eco-attributes of wooden-material (see online version for colours)



The horizontal and vertical bars in the plot shown in Figure 3 represent the uncertainty in the data (Ashby, 2009). As seen from Figure 3, the water usage (cm^3-water/cm^3-wooden material) is quite high because of the fact that for growing a tree a substantial amount of water is needed. It has been found after a calculation that around 680 cm^3 of water (on an average) is needed for producing 1 cm^3 of wooden-material (the value of R_{RP} for wooden-material-based RP technology). In addition, 0.29 g of CO_2 emission takes place for producing 1 cm^3 of wooden-material (the value of C_M for wooden-material-based RP technology). Therefore, if one builds a prototype that needs, say 100 cm^3 of fresh wooden-material, the prototype results in 29 g of CO_2 emission and 68 litres of water consumption on top of it (i.e., 100 cm^3 of wooden-material).

Figure 4 Eco-attributes of polymeric material (see online version for colours)



On the other hand, for building a physical model by using SLA, various polymers and binding materials are used. It is worth mentioning that the polymer and the binding material (i.e., the model-building material) is actually a photosensitive material (photo-resin) and the model-building process solidifies it by using a laser. The same database (CES Selector, Version 5.1.0, http://www.grantadesign.com) has been searched and CO_2 footprint and water usage of primary production of 288 selected polymers (epoxy, rubber, and polyester) have been determined. The results are plotted in Figure 4.

The horizontal and vertical bars in the plot shown in Figure 4 represent the uncertainty in the data (Ashby, 2009). The water usage of primary production of polymers is similar to that of wooden materials, but the CO_2 footprint is quite high this time, indicating the fact that the polymers are less environmentally-friendly compared to the wooden-materials. It has been found after a calculation that about 395 cm^3 of water (on an average) is needed for producing 1 cm^3 of polymeric material (the value of R_{RP} for SLA-based RP technology). In addition, 5.9 g of CO_2 emission takes place for producing 1 cm^3 of polymeric material (the value of C_M for SLA-based RP technology). Therefore, if one builds a prototype that needs 100 cm^3 of polymeric material, the prototype results in 590 g of CO_2 emission and 39.5 litres of water consumption on top of it (i.e., 100 cm^3 of polymeric material).

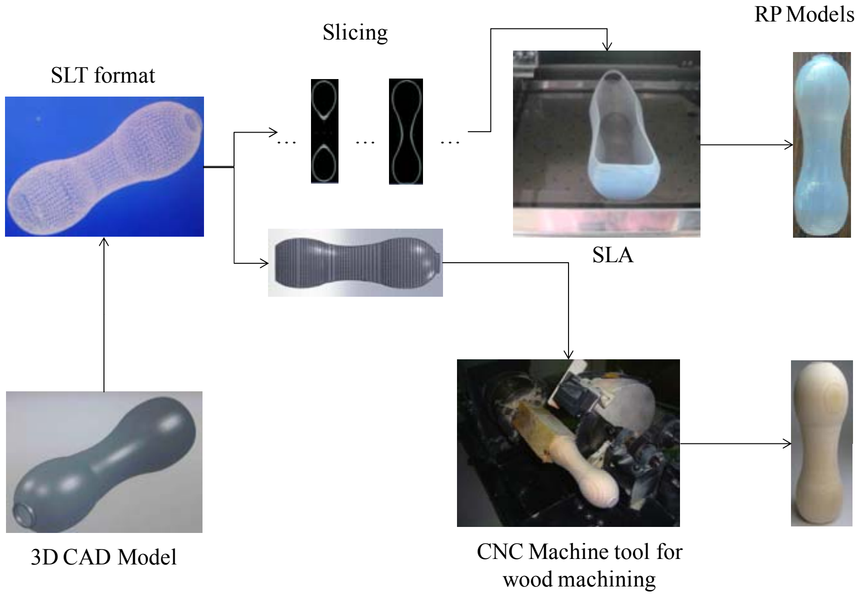
It is worth mentioning that for the same external volume of a physical model, the amount of fresh polymeric material is quite low compared with that of wooden-material because of the nature of respective manufacturing processes – see the numerical results in the following sections.

5 Effect of model-building process

Sustainability index S_{RP}, as defined in the above, depends not only on the model-building material (C_M and R_{RP}), but also on the model-building process. In particular, two main parameters of model-building process, E_P and V_M, affect S_{RP} significantly – see equations (2) to (6). This section deals with determining E_P and V_M for two different RP technologies, A and B, as mentioned before. Note that the actual figure of E_P does not match the theoretical one, and the type of equipment may play a role too (Baumers et al., 2011a, 2011b). Therefore, experiments must be carried out to determine the energy consumption of RP model-building process (E_P). The experimental setup used in this study is illustrated in Figure 5.

As seen from Figure 5, first, a 3D CAD model is produced by using a commercial package. Then, the STL data of the CAD model is generated. The STL data is then sliced into thin layers as required by the additive manufacturing process (SLA) and subtractive manufacturing process (wooden-material-based process). Needless to say that a set of closed contours is generated for each layer. The data of the contours are used to generate commands for controlling the respective RP equipment (SLA or CNC machine tool for woodworking). Accordingly, SLA solidifies the photosensitive resin (one kind of Somos® resin, for this particular case) with the help of a HeCd laser beam. One the other hand, the CNC machine tool for woodworking creates a relative motion between the circular saw and a rectangular wooden block, and removes material from its surroundings as defined by the closed contours of the slicing. The CNC machine for woodworking used here was developed by the Hokkaido Forest Products Research Institute (CNC Machine for Manufacturing Wooden Prototypes, 2012). The experiments have been repeated for different 3D CAD models and energy consumption for each model-building process has been recorded using a watt meter.

Figure 5 Physical model-building processes (see online version for colours)



In general, it is observed that the SLA-based process requires less fresh material (low V_M) because SLA can produce hollow objects by adding the exact amount of material that is needed to produce the external walls of a given 3D CAD model. However, SLA needs a relatively longer time and consumes high energy, as expected (Gutowski et al., 2009; Gutowski, 2010), during the model-building process, because a minimal amount of time and reduced laser dose are needed for proper solidification of the material used (Aoki et al., 2011; Lee et al., 2001). On the other hand, for the wooden-material-based model-building process, the majority of the energy is consumed during the sawdust removal process, not during the material removal process. The wooden prototype has been hand-finished and the energy consumption during hand-finishing operation has not been considered. One of the disadvantages of a wooden-material-based model-building process is that it cannot produce hollow objects and thereby consumes a large amount of fresh material (high V_M) for a given external volume of a 3D CAD model.

However, Figure 6 shows a comparison between fresh material needed (V_{MA} and V_{MB}) to build two physical models for the same external volume of a 3D CAD model by SLA and wooden-material-based model-building processes. The results (shown by square dots in Figure 6) underlies a relationship between V_{MA} and V_{MB} expressed as:

$$V_{MB} = 70\left(V_{MA}\right)^{0.55} \tag{14}$$

Comparing equations (12) and (14) yields $\rho = 70$ and $\lambda = 0.55$. This relationship is valid for the given 3D CAD model. One can develop similar models for other CAD models, as needed.

Figure 6 Comparison of fresh material consumption (see online version for colours)

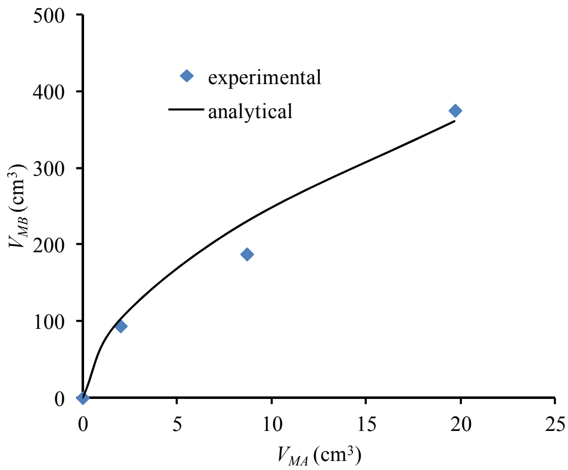


Figure 7 shows the experimental results of energy and material consumption for the SLA-based model-building process for three different scales of the same 3D CAD model. The results imply the following expression:

$$E_{PA} = 0.63(V_{MA})^1 \tag{15}$$

Comparing equations (2) and (15) yields $a_A = 0.63$ and $b_A = 1$.

Figure 7 Energy and fresh material consumption during SLA-based model-building process (see online version for colours)

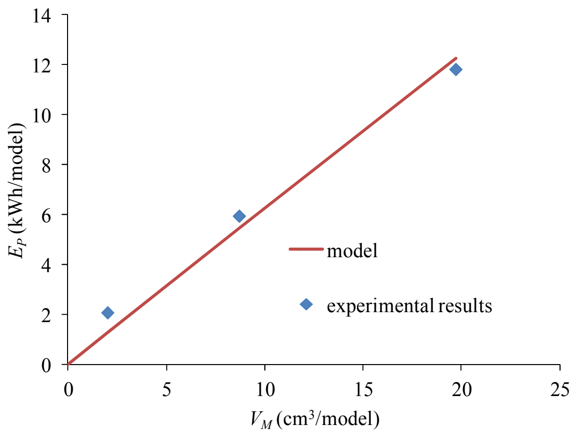
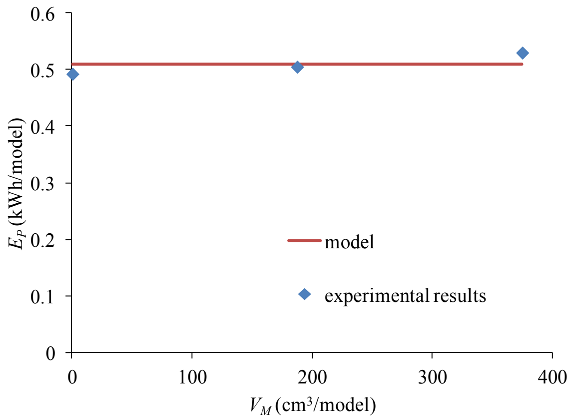


Figure 8 Energy and fresh material consumption during wooden-material-based model-building process (see online version for colours)



On the other hand, Figure 8 shows the results of energy and material consumption of wooden-material-based model-building process for the same CAD models used in the previous case (SLA-based model-building process). As seen from Figure 8, E_P hardly depends on the fresh material consumed. This is because the major part of the energy has been consumed by the peripheral devices (mostly by the mechanism used for removing the sawdust), and not by the wooden material removal devices (circular saw). In this case, a model of E_{PB} versus V_{MB} is a line parallel to V_{MB} axis expressed as

$$E_{PB} = 0.51(V_{MB})^0 \quad (16)$$

Comparing equations (2) and (16) yields $a_B = 0.51$ and $b_B = 0$.

6 Sustainability comparison

This section provides a comparison of sustainability of SLA-based and wooden-material-based RP technologies by using the results described in Sections 3 to 5.

Recall the sustainability of two RP technologies S_{RPA} and S_{RPB} defined in equations (10) and (13), wherein A means SLA-based RP technology and B means wooden-material-based RP technology,.

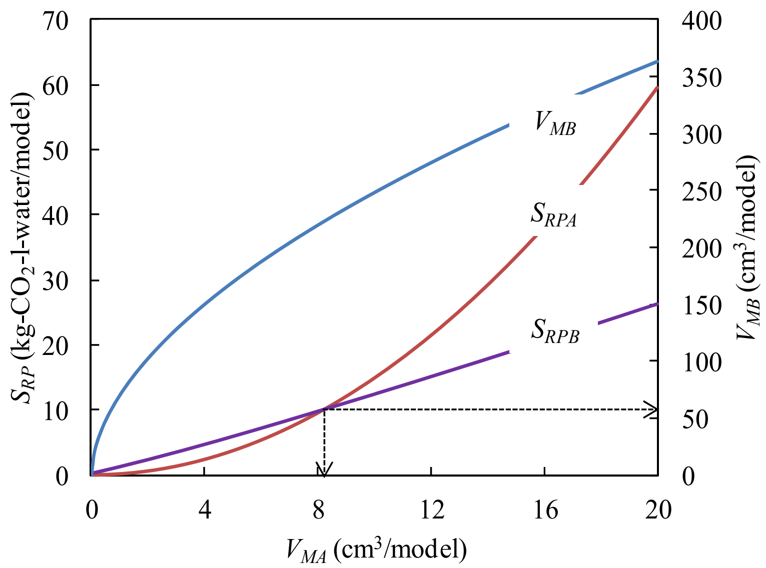
$$S_{RPA} = \alpha_A V_{MA}^2 \left(1 + d_A (V_{MA})^{b_A - 1}\right) \quad \text{(10, repeated)}$$

$$S_{RPB} = \alpha_B \left(\rho^2 (V_{MA})^{2\lambda}\right)\left(1 + d_B \left(\rho^2 (V_{MA})^{2\lambda}\right)^{b_B - 1}\right) \quad \text{(13, repeated)}$$

Table 1 Sustainability parameters

Parameters	*RP technology*	
	SLA-based (A)	*Wooden-material-based (B)*
C_M (kg-CO_2/cm^3 material)	0.0059	0.00029
R_{RP} (l-water/cm^3 material)	0.395	0.680
a	0.63	0.51
b	1	0
f_E (kg-CO_2/kWh)	0.588	0.588
$\alpha = C_M R_{RP}$	0.00233	0.000197
$d = af_E / C_M$	62.7864	1034.069
ρ	70	70
λ	0.55	0.55

Figure 9 Comparison of sustainability of the selected RP technologies (see online version for colours)



The values of the parameters underlying these expressions are listed in Table 1. As listed in Table 1, for the case shown in Figure 5, C_{MA} = 0.0059 (kg-CO_2/cm^3-material), C_{MB} = 0.00029 (kg-CO_2/cm^3-material), R_{RPA} = 0.395 (l-water/cm^3-material), R_{RPB} = 0.680 (l-water/cm^3-material) (see Sections 4). In addition, a_A = 0.63, b_A = 1, [see Section 5, Figure 7, and equation (15)] and a_B = 0.51, b_B = 0 [see Section 5, Figure 8, and equation (16)]. This yields, α_A = 0.00233, d_A = 62.7864, α_B = 0.000197, d_B = 1034.069, since $\alpha = C_M R_{RP}$ and $d = af_E / C_M$ (see Section 3). Moreover, ρ = 70, λ = 0.55 [see Section 5 and Figure 6, and equation (14)]. Using these values, equations (10) and (13) become:

$$S_{RPA} = 0.148654V_{MA}^2 \quad (17)$$

$$S_{RPB} = 0.203918 + 0.96628(V_{MA})^{1.1} \quad (18)$$

Figure 9 shows the plot of S_{RPA} and S_{RPB} in equation (17) and (18), respectively, in addition to V_{MB} in equation (14), with respect to V_{MA}. From Figure 9, it is clear that there is a critical volume where $S_{RPA} = S_{RPB}$. For this particular case, it is found that the critical volume of fresh material is about 8 cm^3 for SLA-based RP technology. On the other hand, the critical volume of fresh material is around 220 cm^3 for wooden-material-based RP technology. It is also learnt that if RP model requires less than 8 cm^3 of fresh photo-resins, it is better to build it by SLA-based RP technology. If the model requires more than 8 cm^3 of fresh photo-resins, it is better to build it by the alternative technology, i.e., wooden-material-based RP technology.

7 Concluding remarks

The following conclusions are made from this study:

- An analytical index is developed to quantify the sustainability of a RP technology in terms of both materials and resources needed for the primary production of model-building materials and energy consumption during the model-building processes.
- Such RP technologies as SLA-based additive RP technology and wooden-material-based subtractive RP technology are compared using the presented sustainability index. The parameters needed to calculate the value of sustainability index are determined by performing experiments using a conventional RP equipment (SLA) and a special RP machine (i.e., a CNC machine for woodworking).
- There exists a critical amount of fresh material for which both wooden-material-based RP technology and SLA-based RP technology produce the same environmental burden.
- From the viewpoint of CO_2 footprint of primary material production and CO_2 emission of model-building process, wooden-material-based RP technology is better than the SLA-based RP technology.
- From the viewpoint of resource depletion (i.e., materials and water usages), SLA-based RP technology is better than the wooden-material-based RP technology.
- The wooden-material-based RP technology can be improved further by developing machine tools for woodworking capable of producing hollow objects. On the other hand, SLA-based RP technology can be improved further by developing new polymers that solidify faster than the currently used photosensitive resins. Thus, in general, the sustainability of RP can be improved further either by developing new RP equipment or by developing new materials.

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